Decoherence in BEC

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Phys. Rev. A **62**, 13607 (2000)

Quantum superpositions

- <u>Microscopic superpositions:</u>

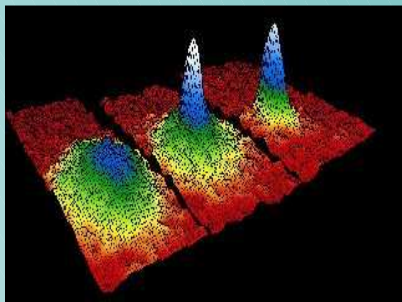
✔ Cavity QED: 2 photons (M. Brune *et al*, PRL **77**, 4887 (1996))

✔ Ion traps: 4 ions (C. Myatt *et al,* Nature **403**, 269 (2000))

- <u>Macroscopic superpositions:</u>

✔ Rf–SQUIDS: 10^9 Cooper pairs (J. Friedman *et al,* Nature 406, 43 (2000))

What about Bose–Einstein condensates?



BEC in a snapshot

- Weakly interacting bosons at $T<T_c$ show a macroscopic occupation of the ground state: quantum degeneracy (Bose–Einstein 1925)

$$n\lambda_T \approx 1$$

- BEC achieved experimentally in 1995 in dilute atomic vapors (Rb, Na, Li, H)

- Breakthroughs: mixtures, atom lasers, vorteces

- Theoretical description: Gross–Pitaeskii equation

BEC Schroedinger Cats

Proposals: J. Cirac *et al*, PRA **57**, 1208 (1998)
D. Gordon *et al*, PRA **59**, 4623 (1998)
J. Ruostekoski, cond–mat/0005469

✔ Two BECs of atoms in different internal states (A and B) + Josephson coupling λ

$$H_c = \epsilon_g(a^\dagger a + b^\dagger b) + \frac{u_c}{2}(a^\dagger a^\dagger aa + b^\dagger b^\dagger bb) + v_c(a^\dagger b^\dagger ab) - \lambda(a^\dagger b + b^\dagger a)$$

✔ Interspecies two–body collisions stronger than intraspecies collisions $(v>u)\rightarrow$ phase separation (immiscibility)

✔ "Purity" condition: $\left(\frac{\lambda}{N(v-u)}\right)^N \ll 1$

Lowest energy subspace contains two macroscopic quantum superpositions

$$\boxed{|\pm\rangle = \frac{1}{\sqrt{2}}[|N,0\rangle \pm |0,N\rangle]}$$

Preparation: start with all atoms in state A, apply Josephson coupling for some appropriate time, then turn it off. The final state is a Schroedinger cat.

Is the cat long–lived?

Decoherence due to the thermal cloud

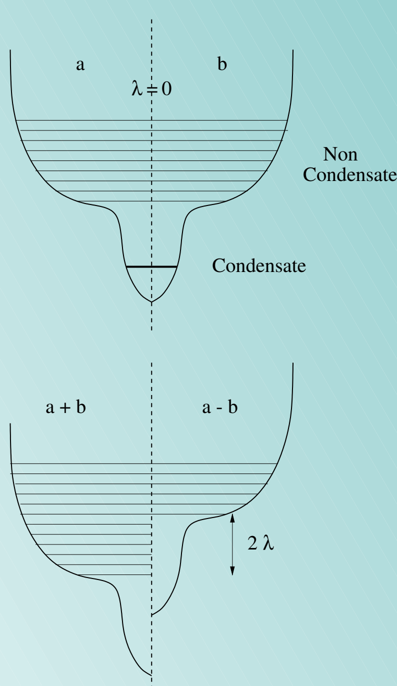
$$H_{\rm E} = \sum_s [\epsilon_s (a_s^\dagger a_s + b_s^\dagger b_s) - \lambda (a_s^\dagger b_s + b_s^\dagger a_s)]$$

After the transformation

$$S_s = \frac{a_s + b_s}{\sqrt{2}}, \qquad O_s = \frac{a_s - b_s}{\sqrt{2}}$$

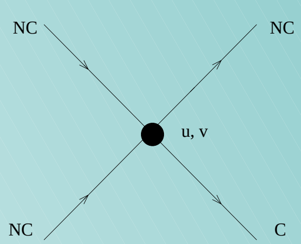
The environment Hamiltonian becomes diagonal:

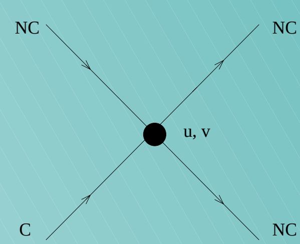
$$\rightarrow H_{\rm E} = \sum_s [(\epsilon_s - \lambda) S_s^\dagger S_s + (\epsilon_s + \lambda) O_s^\dagger O_s]$$



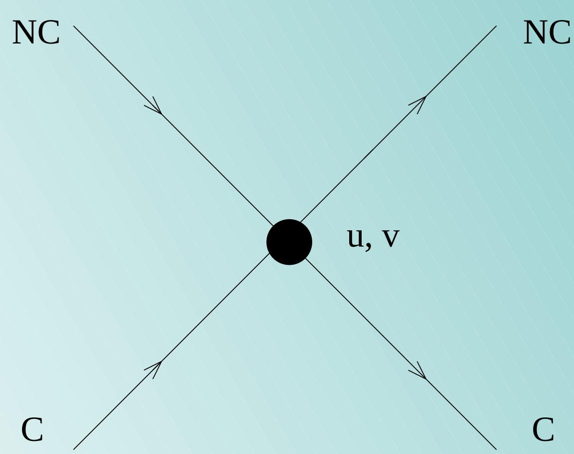
System–bath interactions

- Two–body inelastic collisions. They are $O(z^2)$, where $z = \exp(\beta\mu)$ is the fugacity.





- Two–body elastic collisions. They are $O(z)$. For small fugacity (when the gap between condensate and non–condensate single–particle levels is bigger than $k_{\rm B}T$) these diagrams dominate. Also they give the leading $O(N^2)$ contribution to the decoherence rate.



DFS in BEC

When $2\lambda \gg k_{\mathrm{B}}T$, the antisymmetric environmental states O_s are nearly empty. Only the symmetric ones S_s are occupied. These states don't distinguish between A and B.

→ Collisions involving symmetric thermal states don't destroy the quantum phase coherence of the Schroedinger cat

$$[V, \mathcal{P}_{[\alpha|N,0\rangle+\beta|0,N\rangle]}] = 0$$

Any superposition $\alpha|N,0\rangle + \beta|0,N\rangle$ is an eigenstate of the interaction Hamiltonian, and will retain its phase coherence

↓

Decoherence–free pointer subspace, aka DFS

But ...

When antisymmetric states begin to be occupied, states in the DFS will decohere.

Decoherence rate

$$\boxed{t_{\text{dec}}^{-1} > 16\pi^2 \left(4\pi a^2 \frac{N_{\text{E}}}{V} v_T\right) N^2}$$

Where N^2 is the main factor which makes the decoherence rate large. It is the distance squared between macroscopically different components of the cat.

The factor in brackets is a scattering rate of a condensate atom on a non–condensate atom – the very process by which the environment learns about the quantum state of the condensate.

$$T = 1\mu\text{K},\ w = 50\text{Hz},\ a = 5\text{nm},\ v_T = 10^{-2}\text{m/s},\ V = 10^{-15}\text{m}^3$$

$$t_{\text{dec}} \approx 10^5\text{sec}/(\text{N}_\text{E}\text{N}^2)$$

For $N = 10^3$ and $N_{\text{E}} = 10$, we get $t_{\text{dec}} \approx 10^{-2}\text{sec}$

Trap engineering I

We propose the following scenario, which is a combination of present day experimental techniques

✔ Start with the usual magnetic trap and superimpose an optical trap to form the dip. Typical value for the fugacity at $T = 1\mu\mathrm{K}$ is $z = \exp(-1.5)$ (S.Stamper–Kurn *et al*, PRL **81**, 2194 (1998)).

✔ Open the big trap and let the non–condensed atoms disperse away (S.Stamper–Kurn *et al*, PRL **80**, 2027 (1998)) After this, there may still be a band ΔE of bound states at the "mouth" of the dip that could still be harmful.

✔ Apply the Josephson–like coupling λ. Typical value is $\lambda = 1\mathrm{kHz}$ (D.Hall *et al*, PRL **81**, 1539 (1998)).

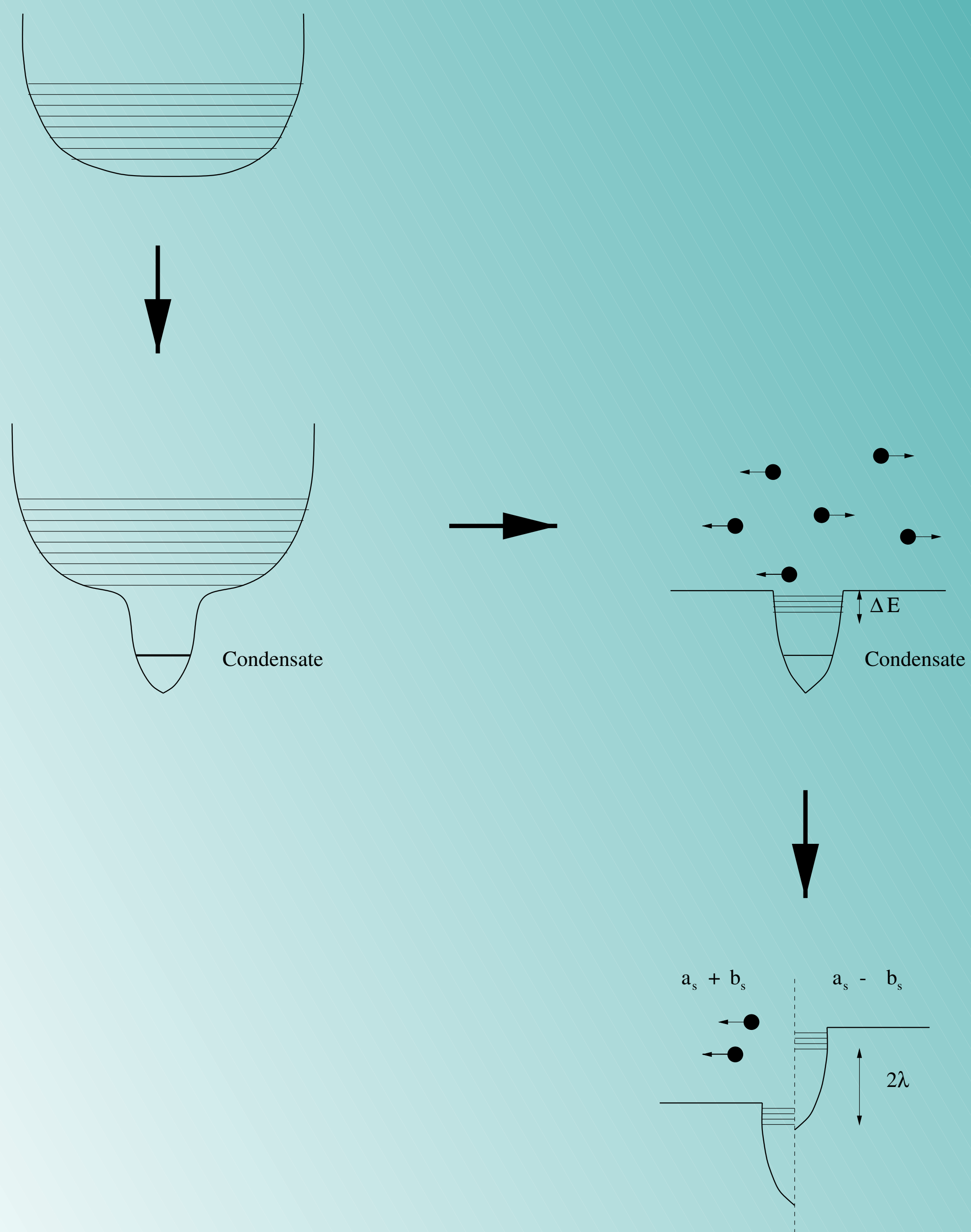
$\Delta E \ll 2\lambda$ Perfect "symmetrization" limit

After symmetrization, the decoherence rate reads

$$t_{\mathrm{dec}}^{-1} > 16\pi^2 \left(4\pi a^2 \frac{N_{\mathrm{E}}^{\mathrm{O}}}{V} v_T\right) N^2$$

Where $N_{\mathrm{E}}^{\mathrm{O}}$ is the final number of atoms in the antisymmetric states.

Trap engineering II



Other sources of decoherence

- **Ambient magnetic fields** (when A and B have different magnetic moments). Use $|F, M_F\rangle = |2,1\rangle, |1,-1\rangle$ states of $^{87}\mathrm{Rb}$ (E.Cornell *et al*, J.Low Temp.Phys. **113,** 151 (1998)).

- **Different scattering lengths** (typically 1%). Symmetrization can improve decoherence time in two orders of magnitude.
(W.Ketterle *et al*, con−mat/9904034).

- **Three−body decay.** BECs have finite lifetimes due to collisions between three particles. For $N = 10^4$ one atom is lost per second. Increasing the dip radius may decrease decoherence rate (loss rate scales as density squared) (D. Stamper−Kurn *et al*, PRL **81**, 2194 (1998)).